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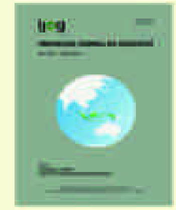
INDONESIAN JOURNAL ON GEOSCIENCE

Geological Agency

Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id

ISSN 2355-9314, e-ISSN 2355-9306



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FRACTAL DIMENSION ANALYSIS AND EARTHQUAKE REPEATED PERIOD ESTIMATION IN SUMATERA FAULT ZONE CASE: BENGKULU-LAMPUNG-SUNDA SEGMENT

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[Abstract] - An earthquake seismicity parameter study has been conducted in the southern part of the Sumatra Fault Zone (SFZ) for the period 1919 to 2019 with a hypocenter depth of 120 km and magnitude ≥ Mw 4. The research area is divided into three segments, Bengkulu segment, Lampung segment and Sunda segment, respectively. This study aims to evaluate the seismicity parameters in the form of a-value, b-value, fractal dimension and probabilities of earthquake recurrence period. Frequency-magnitude correlation statistical approach introduced by Gutenberg-Richter is used to calculate of seismicity parameters based on catalogue data obtained from USGS. An a-value variation of 4.44 to 5.63 is obtained, which indicates the most dominant seismic intensity. b-value of 0.66 to 0.80 correlate with high-stress levels, the level of spatial heterogeneity on the SFZ and the probabilities of bigger earthquakes in the future. The calculation of fractal dimension of 1.3 to 1.6 indicates an earthquake distribution pattern caused by a single fracture zone along the SFZ. The fracture zone is located on the left and right of the SFZ, which may not have been connected. In addition, the calculation result of earthquake recurrence period with magnitude moment (Mw) ≥6.5 indicate that an earthquake will occur for a hundred years period is more than 5 event in the Bengkulu segment, 3 event in the Lampung segment and 2 event in the Sunda segment, while the probabilities of an earthquake with magnitude moment ≥7.5 along the southern SFZ is more than 2 times.
[Keywords] magnitude moment, a -value, b-value, seismicity, hypocentre.

[Abstrak] - Studi parameter seismisitas kegempaan telah dilakukan di bagian selatan *Sumatra Fault Zone* (SFZ) periode 1919 hingga 2019 dengan kedalaman hiposenter kurang dari 120 km dan magnitude momen (Mw) ≥4. Area penelitian dibagi menjadi tiga segmen masing-masing; segmen Bengkulu, Lampung dan Sunda. Penelitian ini bertujuan untuk mengevaluasi parameter seismisitas *a-value*, *b-value*, dimensi fraktal, dan probabilitas periode perulangan gempa dengan magnitude ≥6.5. Korelasi antara frekuensi dan magnitudo gempa dengan pendekatan statistik yang diperkenalkan oleh Gutenberg-Richter digunakan untuk menghitung parameter seismisitas berdasarkan data katalog yang diperoleh dari USGS. Diperoleh nilai variasi *a-value* 4,44-5,63 yang menunjukkan intensitas seismik yang paling dominan, sedangkan *b-value* 0,66-0,80 berkorelasi dengan tingginya tekanan yang terjadi pada zona gempa di SFZ sehingga meningkatkan probabilitas gempa yang lebih besar di masa yang akan datang. Hasil perhitungan nilai dimensi fractal sebesar 1.3 s/d 1.6 mengindikasikan pola kegempaan diakibatkan oleh zona *fracture* tunggal disepanjang SFZ. Zona *fracture* tersebut tersebar kearah kiri dan kanan SFZ yang kemungkinan belum terkoneksi satu sama lain. Selain itu hasil perhitungan periode perulangan gempa dengan nilai magnitude ≥6.5 mengindikasikan bahwa akan terjadi gempa dalam periode seratus tahun sebanyak lebih dari 6 pada segment Bengkulu, 3 kali pada segment Lampung dan 2 kali pada segment Sunda.

Sedangkan peluang terjadinya gempa dengan magnitudo ≥7.5 di sepanjang SFZ bagian selatan sebanyak lebih dari 2 kali.

Kata kunci: momen magnitudo, *a-value, b-value,* seismisitas, hiposentre.

INTRODUCTION

Bacground

Various tectonic processes become one of the main factors in the geomorphological patterns on the earth's surface, such as fracture and fault. The earthquake, as one of the effects of the tectonic process, becomes a particular concern because of the substantial and great danger posed. Earthquakes as complex phenomena can also be measured using the concept of fractals (Luginbuhl et al., 2018). Based on plate tectonic theory, crustal deformation occurs at plate boundaries and becomes the centre of ocean plate widening, subduction zones, and fault transformation. Displacement and transformation of the fault in the subduction zone will produce disruption in the form of shocks as a form of energy release. However, crustal deformation is more complex and is usually associated with relatively more extensive deformation zones.

The Bengkulu earthquake (2000), the Aceh earthquake (2004), the Nias earthquake (2005), the West Sumatra earthquake (2007), the Bengkulu earthquake (2007) and the Lampung earthquake (2019) are potentially become a series of the precursor activity to a much bigger one in the Southern area, between the Lampung Strait and the South Sunda Strait. The earthquake that occurred in this region has claimed many lives and property (Rahmat et al., 2018). The high seismic activity in Sumatra is shown on the earthquake map (Figure 2). The distribution of regional seismicity is often considered clustered so that the seismic pattern is not Poisson (De Natale et al., 1988).

The strength of an earthquake can be estimated using a magnitude scale. Magnitude generally depends on earthquake frequency so it can involve fractal techniques to understand the characteristics of the earthquake area. Also, the temporal behaviour of seismicity related to fractal geometrical clustering (Smalley et al., 1987). (King, 1983), (D. L. Turcotte, 1986) and (D.L. Turcotte, 1986) develop fractal methodologies for tectonic and seismic activities. Various tectonic processes are directly related to the shape of the surface topography on the earth. Seismicity is classic examples of complex phenomena that can be measured using the concept of fractals(D. L. Turcotte, 1986), (D.L. Turcotte, 1986), (Luginbuhl et al., 2018)

This study aims to determine the fractal dimension of the hypocenter from a series of earthquakes that occurred in the southern area of the Sumatra Fault Zone (SFZ) from 1919 to

2019. The steps in this study include; (i) inventory of earthquakes in the period 1919 to 2019 based on data obtained from the USGS, (ii) selection of earthquake epicenter areas based on PKF zones (iii) selection of earthquake hypocenter depths (<120 km) (iv) calculation of a-value and b-value, (v) calculation of fractal dimensions, and (vi) Estimation of future earthquake recurrence period.

Seismicity History of the Lampung-Bengkulu Subduction Zone.

The history of the earthquake in these two provinces is not new, on 29 January 1833, a massive Mw 8.9 earthquake occurred in Bengkulu. On 4 June 2000, an Mw 8.3 earthquake occurred in the Bengkulu offshore which killed 85 people and seriously injured more than 600 people. In September 2007 another series of earthquakes shook Bengkulu, first occurring on 12 September 2007 with a magnitude of 8.4 and hypocenter depth of 30 km. The first significant aftershock (Mw of 7.9) occurred on 13 September 2007, with a hypocenter depth of 10km. The 2007 earthquake killed 26 people and caused damage to buildings and infrastructure. From 12 September to 24 October 2007, there were 109 aftershocks, nine of them with Mw ≥6 and Mw > 4 aftershocks (Zen et al., 2008).

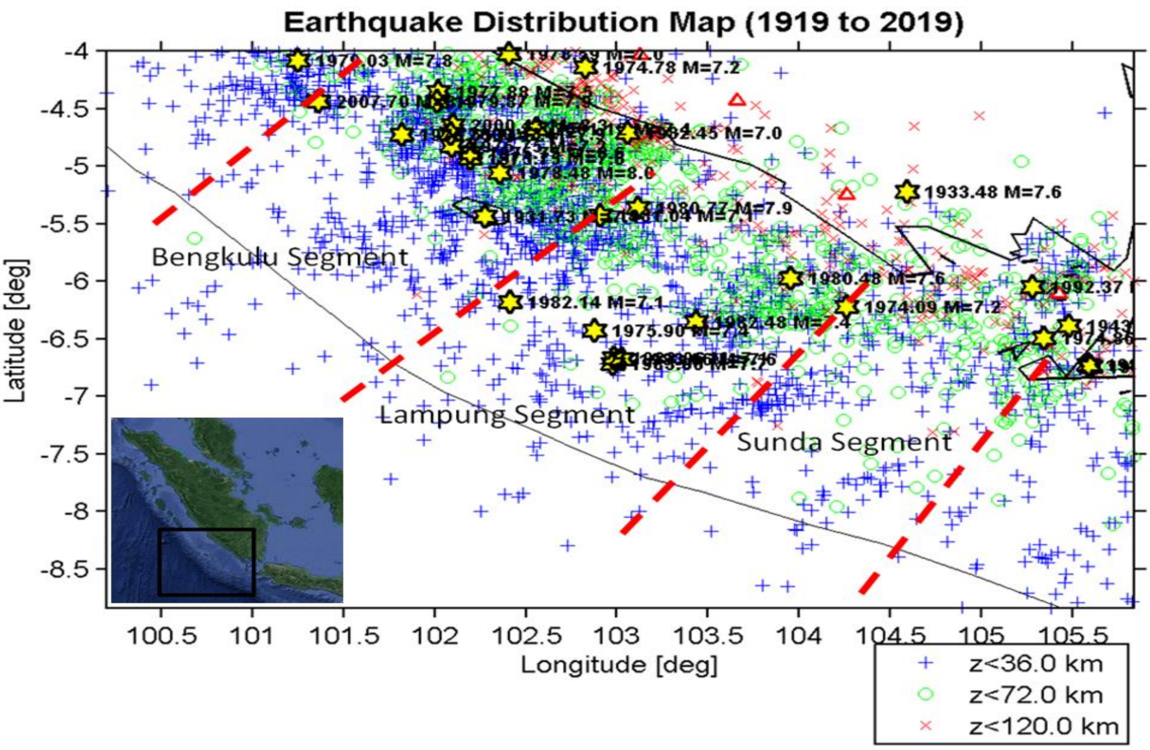

Figure 1. Historical seismicity of the SFZ subduction zone in the Bengkulu-Lampung-Sunda segment (source: USGS).

In the western part of Indonesia, the tectonic style manifests itself as a tectonic subduction zone, an oblique subduction underneath Sumatra with a small subduction angle (Zen et al., 2008). The Sumatra Fault Zone (SFZ) is a result of the stress distribution in this subduction zone. This fault zone cuts through the entire length of Sumatra's west coast (1,625 km). SFZ is a right-lateral strike-slip fault which divided into 11-13 segments (Zen et al., 2008). The SFZ segment at the southern end is located on offshore Lampung and intersects the Java Trench in the south of West Java. The 1994 Liwa earthquake occurred on February 15, 1994, which caused severe damage in Liwa, West Lampung Regency with an earthquake centred on the Semangko Fault. Nearly all permanent buildings in Liwa were destroyed because of it. More than 196 people from several villages and sub-districts in West Lampung were killed, while the number of injured victims reached almost 2000 people and 75 thousand people become homeless.

This research objective is to determinate the pattern of earthquake triggers in the southern part of the Sumatra subduction zone, which can be divide into Bengkulu segments, Lampung segments and Sunda segments. The approach used is based on fractal dimension calculations. The steps taken in this study include; (i) earthquake inventory based on seismicity data obtained from USGS (Mw ≥4), (ii) earthquake epicenter segmentation (Bengkulu-Lampung-Sunda segment), (iii) calculation value of fractal dimension of hypocenter.

METHODS

Mandelbrot (1967) developed and applied the concept of fractals widely in the fields of geology and geophysics based on pre-existing fractals. The mathematically fractal theory is a series of construction events that can be quantized according to the following equation,

$$N_i = \frac{C}{r_i^D} \tag{1}$$

where N_i is the number of objects (fragments) with linear dimensions r_i, C is constant of proportionality, and D is the fractal dimension.

The fractal dimension can be an integer, in this case equivalent to the Euclidean dimension, where the Euclidean dimension of a point is zero. The line, plane, and cube segment is valued by 1, 2, and 3 respectively. In general, the fractal dimension is not an integer but a fractional dimension. The zero-order is a line segment in length unit (D.L. Turcotte, 1986). Figure 2(a) and 2(b) are line segments valued by one unit length (zero-order), figure 2(c) and 2(d) fractal dimension segments line of 1, figure 2(e) and 2(f) show line segments with fractal dimension of 0.6309 and 0.6309 respectively (Turcotte, 1998).

The fractal dimension D can be calculated based on the following equation,

$$D = \frac{\ln(N_{i+1}/N_i)}{\ln(r_i/r_{i+1})} = \frac{\log(N_{i+1}/N_i)}{\log(r_i/r_{i+1})} \tag{2}$$

where ln is e based logarithm and log is 10 based logarithm.

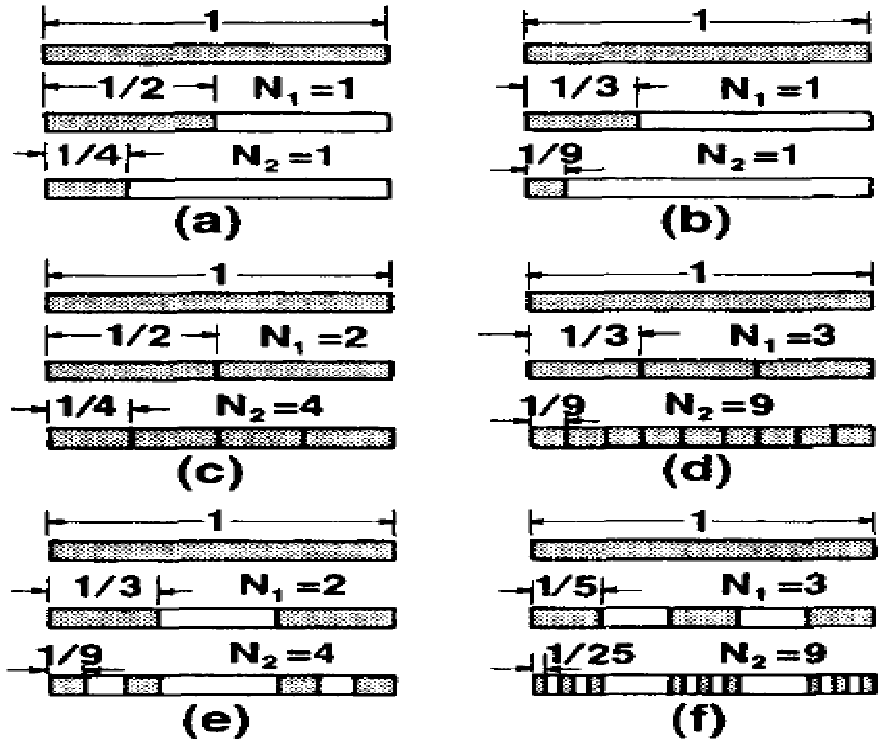

Figure 2. Illustration of six 1D fractal constructions (Turcotte, 1986).

The concept of fractals geometry applied to line segments can also be applied to a plane or area segments. Fractal dimensions in the case of plane can be described as follows,

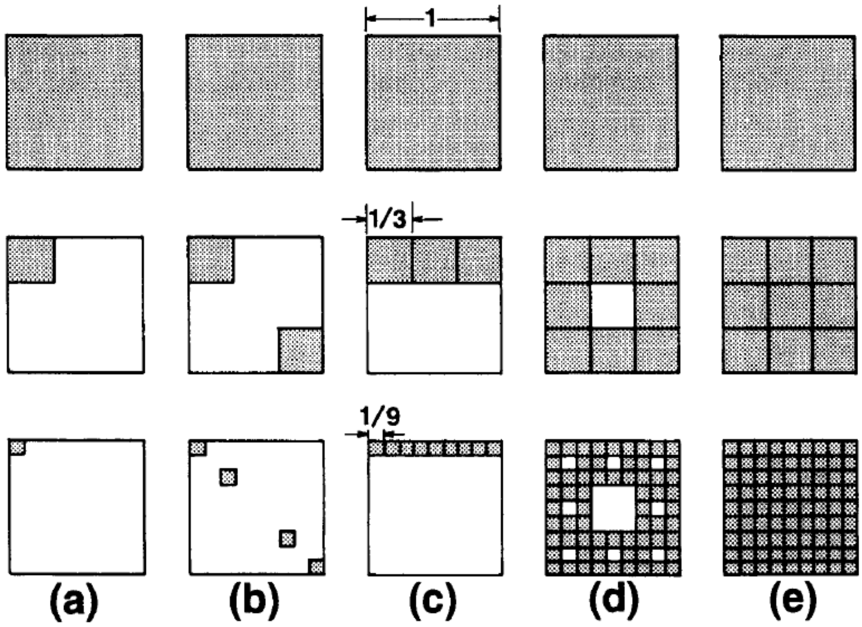

Figure 3. Fractal geometrical concept in simple plane (Turcotte, 1986).

Six initial steps of the construction on fractal geometry concept is shown on Figure 3(a) only one square is maintained (fractal dimension of 1), figure 3(b) fractal dimension of 0.6309, figure 3(c) the remaining planes will be lines (fractal dimension of 1); figure 3(d) only the central square is deleted (fractal dimension of 1.8928), figure 3(e) shows the value of the Euclidean dimension of an area because when all blocks are maintained it will produce units of area (fractal dimension of 2) (Turcotte, 1998).

The construction can be designed to produce fractal dimensions between 0 to 2. The application of 1D and 2D such as figures (2) and (3) can be expanded into 3D shapes like the two models in figure (4).

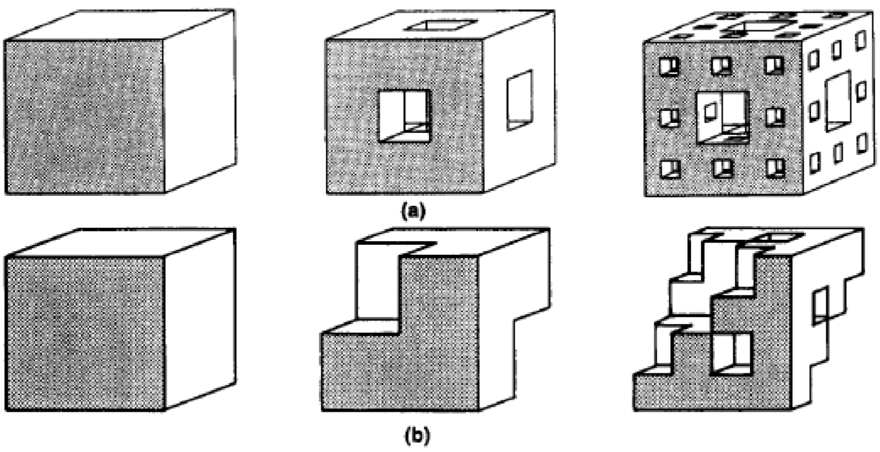

Figure 4. Fractal dimensional concept in 3D (Turcotte, 1998).

Figure 4(a) is a solid cube with a fractal dimension of 2.7268, figure 4(b) is a solid cube with a fractal of 2,585 (Turcotte, 1998). Repeated constructions can be designed to produce fractal dimensions between 0 to 3. The models given above illustrate how geometrical construction can provide non-integer and non-Euclidean dimensions, but not in continuous structure. One model of continuous fractal construction is the Koch triangle which is illustrated in the following,

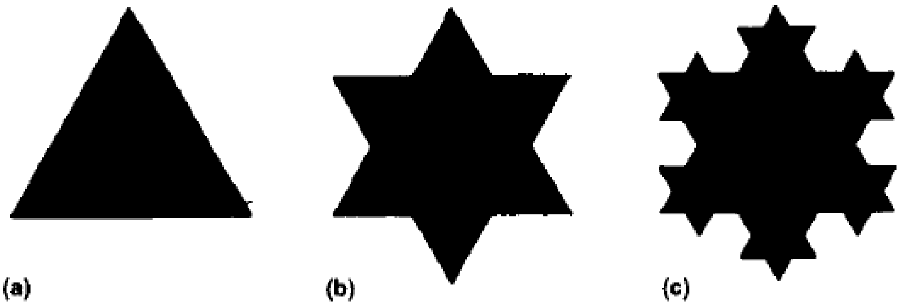

Figure 5. Fractal construction on continuous structure (Turcotte, 1998).

Figure 5(a) zero-order in equilateral triangle with r_o of *3* and N_o of 3, figure 5(b) first order equilateral triangle with side length r_1 of *1/3* placed in the middle of each side, now there are 12 sides, so N_1 is 12, figure 5(c) construction of the second order by placing an equilateral triangle r_2 of *1/9* in the middle of each side so N_2 becomes of 48. Based on equation (2), a fractal dimension of 1.26186 is obtained (Turcotte, 1998).

From the basic concept of the one and two dimensions fractal dimension, can proceed to unlimited construction and mathematically written as,

$$P_i = r_i N_i \tag{3}$$

The fractal P_i parameter calculation is based on the length of the sides in the *i-th* sequence and *N* as the number of sides. If equation (3) substituted into equation (1) is obtained,

$$P_i = \frac{C}{r_i^{D-1}} \tag{4}$$

The application of fractal dimension calculation in the Koch triangle case is described as,

$$D = 1 + \frac{\log(P_{i+1}/P_i)}{\log(r_i/r_{i+1})} \tag{5}$$

RESULT

USGS earthquake catalogue data along the Bengkulu-Lampung-Sunda SFZ segment from 1919 to October 2019 was used, with a total 2010 (≥4 Mw) earthquake events and maximum hypocenter depth of 120 km. Where the entire event of each segment consists of; (i) Bengkulu segment 1174 earthquake events, (ii) 629 events in Lampung segment and (iii) Sunda segment 207 events. Figure (6) shows the earthquake frequency in each segment based on the magnitude value.

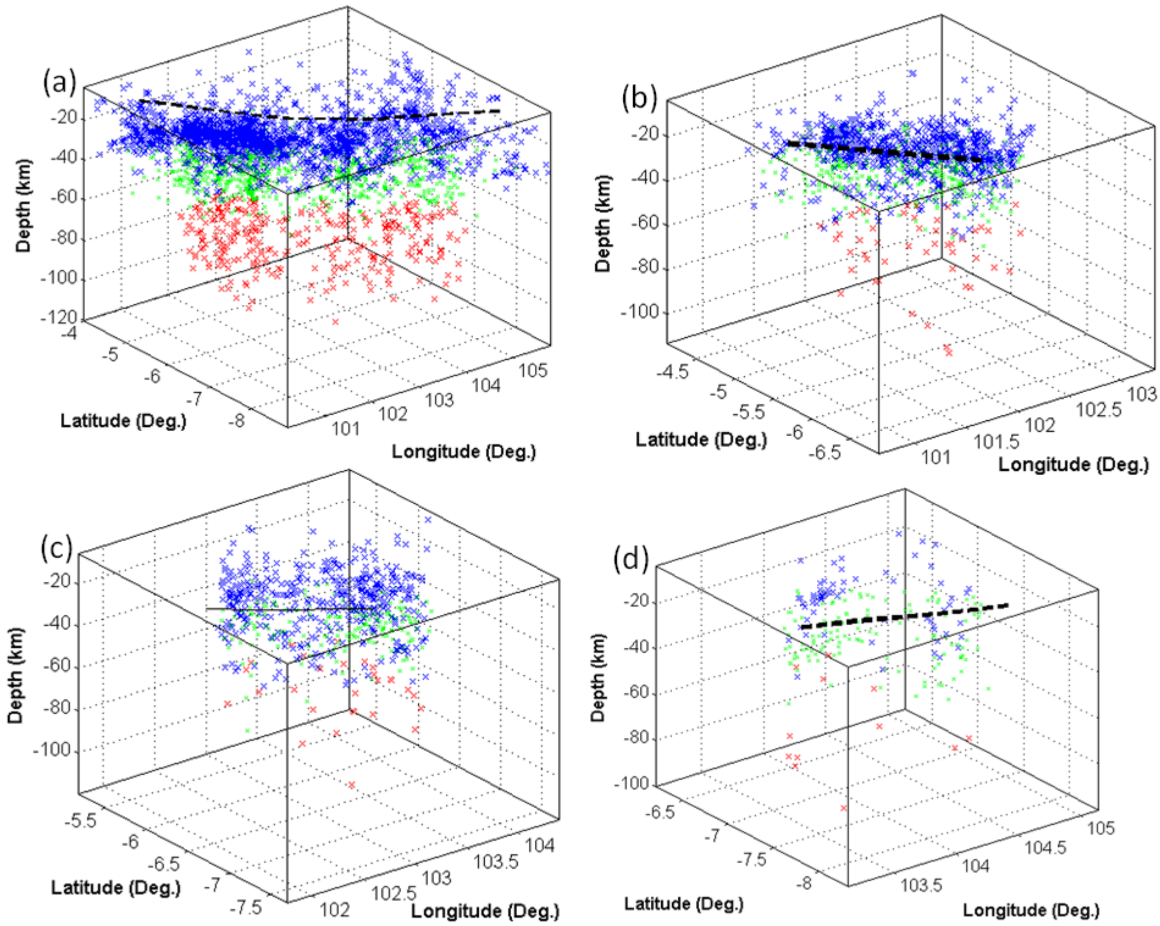

Figure 6. Distribution of earthquake hypocenter (a) Bengkulu-Lampung-Sunda segment, (b) Bengkulu segment, (c) Lampung segment and (d) Sunda segment.

The seismicity history of the study area is shown in Figure 7. indicates the number of earthquake events per year, where earthquake events reached more than 400 in 2000 (see Figure 7a). From Figure 7b shows more than 700 events with hypocenter depth at 30 km. While from the distribution, more than 200 seismic events based on period, hypocenter depth and magnitude of ≥4 Mw can be seen in Figure 7.

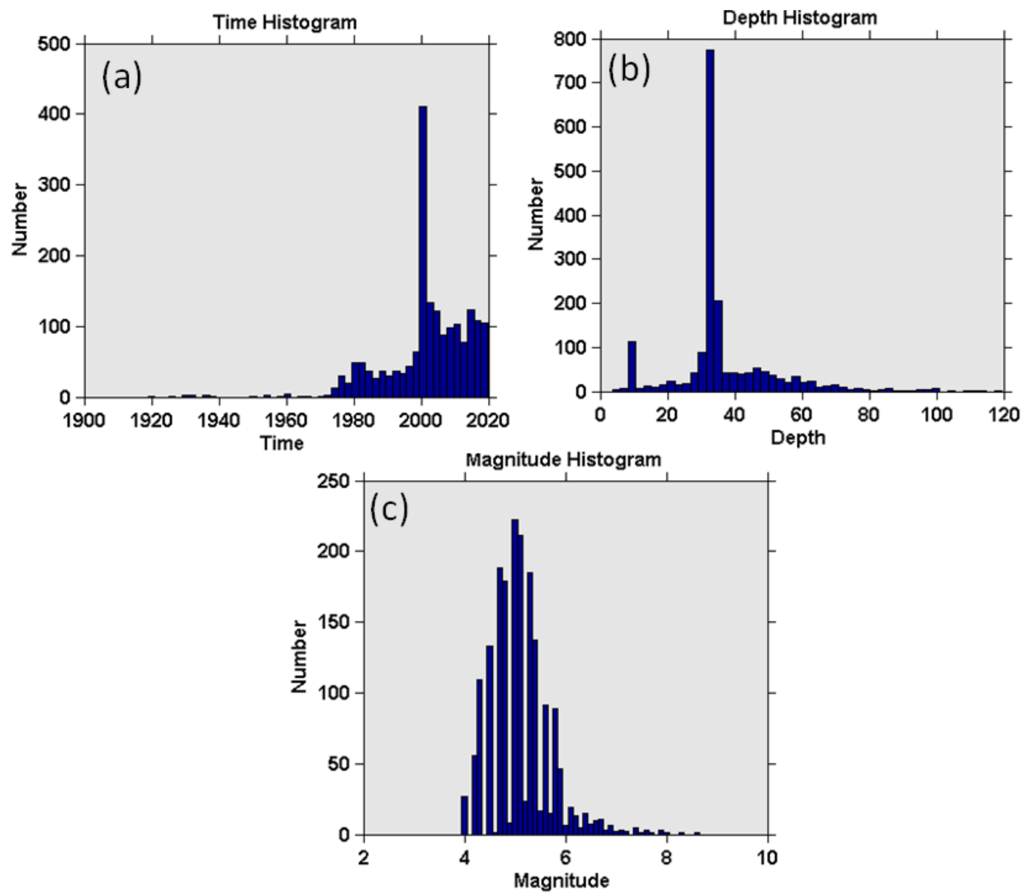

Figure 7. Historical seismicity in the Bengkulu-Lampung-Sunda segment from 1919 to 2019 with magnitude moment ≥4, (a) earthquake cumulative base on years, (b). earthquake cumulative base on depth, (c) earthquake cumulative base on magnitude

By applying the Gutenberg and Richter approach (Gutenberg and Richter, 1945) in the form of a statistical correlation that correlates the frequency of earthquakes with the following magnitude,

$$\log(N) = -bm + \log(a) \quad (6)$$

where b and a are constants and N is the number of earthquake events, resulting in the relationship of b-values and constants a. Magnitude (m) is an empirical value of an earthquake size. It can be related to the total energy in the seismic waves produced by the earthquake. A curve, as shown in Figure 8 is obtained based on the results of the subduction segment statistical correlation in this study area.

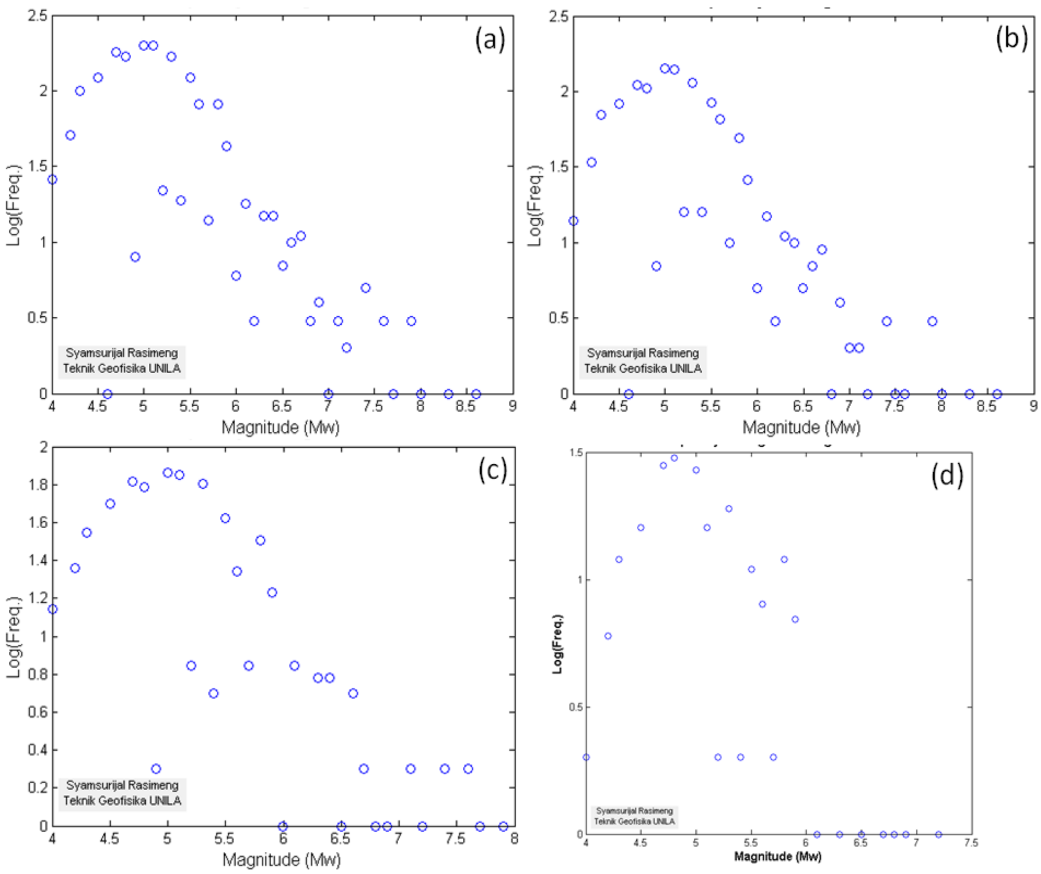

Figure 8. Seismicity frequency at; (a). Bengkulu-Lampung-Sunda segment, (b). Bengkulu segment, (c). Lampung segment, and (d). Sunda segment

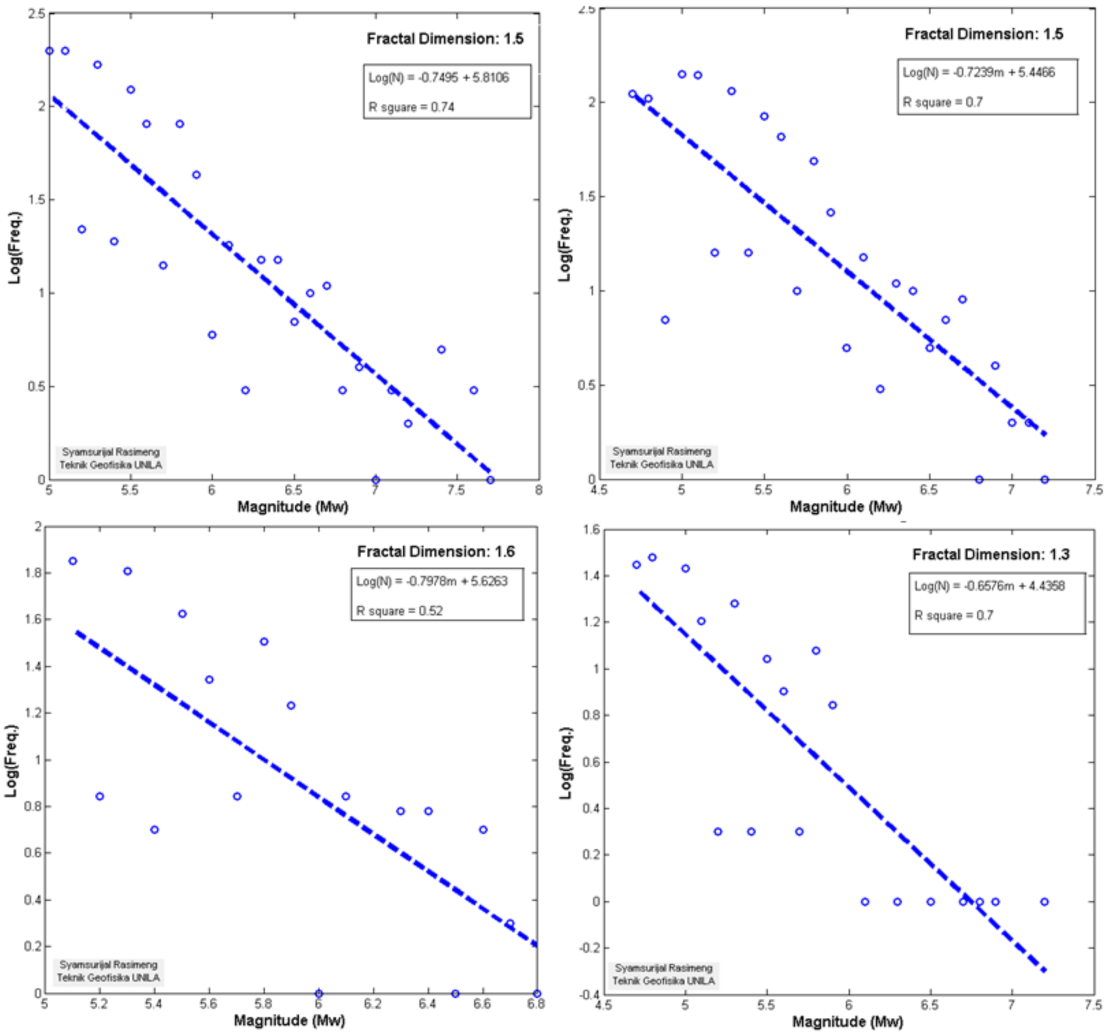

Figure 9. Fractal dimension in each earthquake segment (a) Bengkulu-Lampung-Sunda segment, (b) Bengkulu segment, (c) Lampung segment and (d) Sunda segment.

In theory, *a* logarithmic are defined as seismicity values of earthquakes that most often occur in an area: the higher the value, the more frequent earthquakes with a magnitude of *a*. The *a*-value of 5.80 is obtained based on the calculation in the Bengkulu-Lampung-Sunda segment indicates the distributions of earthquakes with a magnitude of 5.80. Variations in *a*-value of around 4.44 to 5.63 are obtained if the zones are divided into different segments. The highest *a*-value occurred in the Lampung segment of 5,63.

A comprehensive study of the spatial mapping of the frequency distribution was also carried out for all zones. Variations for the *b*-value are obtained at intervals of 0.66 to 0.80 using weighted inversion calculations. Based on (Mogi, 1967) that a low *b*-value is usually correlated with a high-stress level and vice versa. From that relationship, regions with significant heterogeneity correlate with high b-value prices. A high-stress correlation with a relatively low *b*-value indicates that there will be giant earthquakes in the segment with a low

b-value the following year (Singh, 2016). So that among the three segments in this study indicate that the Sunda segment is likely to produce an enormous earthquake in the future.

Some research was introduced the theoretical basis for the c of 1.5 and applies these values to calculate earthquake moments based on magnitude values as ((Kanamori and Anderson, 1975), (Kanamori and Stewart, 1978), (Hanks and Kanamori, 1979)),

$$\log(M) = cm + d \tag{7}$$

where d of 9.1 is a constant.

In certain regions, the number of N earthquakes in a time from fracture zone generally has a large distribution, so the fractal dimension of seismicity is distributed as,

$$D = \frac{3b}{c} \tag{8}$$

based on theoretical relation $c=1.5$,

$$D = 2b \tag{9}$$

The fractal dimension of whole seismic activity is only twice the b-value. The empirical frequency-magnitude relation given in equation (6) correlates with the fractal distribution (Aki, 1981).

DISCUSSION

The results of calculating the hypocenter fractal dimensions in the three segments in this study area have values between 1.3 to 1.6. Fractal dimension analysis shows the pattern of seismicity caused by a single fracture zone along the SFZ. In the fractal dimension, the fracture zones are located on the left and right of SFZ, which may not have been connected. The lowest fractal dimension is in the Sunda segment, so it has the potential to produce high seismic intensity in the future. This is based on the comparison of Bengkulu and Lampung fractal dimensions segment of 1.5 and 1.6 respectively. In addition, the results of the calculation of the earthquake recurrence period with a moment magnitude ≥ 6.5 indicate that an earthquake will occur for a hundred years period is more than 6 times in the Bengkulu segment, 3 times in the Lampung segment and 2 times in the Sunda segment, while the chance of an earthquake with moment magnitude ≥ 7.5 along the southern SFZ is more than 2 times.

Another impact of the high intensity of large earthquakes in this area is the chance of erosion in the coastal area. The erosion rate in the North Bengkulu coastal area is 1.1 to 5.8 m/year, while the amplification factor are 2.35 to 7.99. In addition, it was found that the PGA ranged from 110-179 (Farid et al., 2014).

Frequency-magnitude correlation statistics for the 1904 to 1980 earthquakes have been carried out Abe (1981) and Purcaru and Berckhemer (1982) for the period 1920-1979. The results provided by (Abe, 1981) support the systematic reduction of large earthquake correlation curves, while the results provided by (Purcaru and Berckhemer, 1982) support direct extrapolation of correlation curves with more massive earthquakes. (Pacheco, Scholz, and Sykes, 1992) have considered the extrapolation problem in detail and supported the systematic reduction of large earthquakes.

CONCLUSION

Based on the results of the analysis in this study it can be concluded several things include,

1. The most dominant range of earthquake magnitude in this area is indicated by *a*-value variation of 4.44 to 5.63.
2. The *b*-value results of 0.66 to 0.80 indicate a high level of stress on SFZ and a high chance of occurrence of bigger earthquakes in the future.
3. The fractal dimension of 1.3 to 1.6 indicating the seismicity distribution pattern caused by a single fracture zone along the SFZ, with fracture patterns located on the left and right on SFZ that may not have been connected.
4. The calculation result of earthquake recurrence period with moment magnitude ≥6.5 indicate that an earthquake will occur for a hundred years period is more than 6 times in the Bengkulu segment, 3 times in the Lampung segment and 2 times in the Sunda segment, while the chance of an earthquake with moment magnitude ≥7.5 along the southern SFZ is more than 2 times.

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